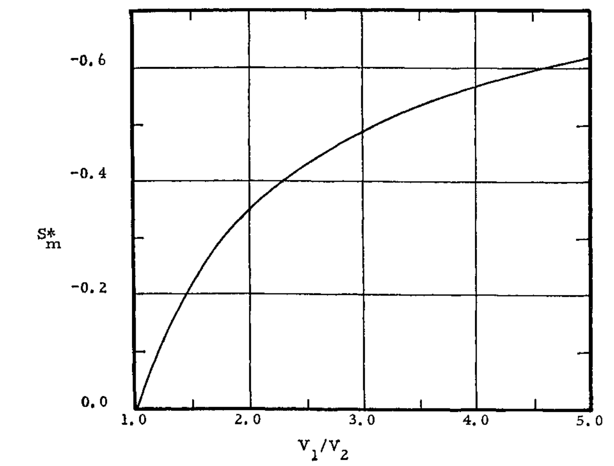

Fig. 2 S_m*, dimensionless location of the point of maximum deceleration.

Eqs. (1) and (5),

$$\rho = \{(1/B)[ke/2\pi r_0(1+e)]^{1/2}\ln(V_1/V_2)\} \times \exp[-kes^2/2r_0(1+e)]$$

and Eq. (6) reduces to the transcendental algebraic equation

$$\ln[V_1/V_2][2r_0(1+e)/\pi ke]^{1/2}\exp[-kes^2/2r_0(1+e)] + s = 0 \qquad (7)$$

Now define a dimensionless distance, $s^* = s[ke/2r_0(1+e)]^{1/2}$, and Eq. (7) becomes

$$[\pi^{-1/2}\ln(V_1/V_2)]e^{-s^{*2}} + s^* = 0$$

the solution of which is s_m^*, the point of maximum deceleration (Fig. 2). Note that there is only a single solution, $s_m^* < 0$.

Corresponding to s_m^* is the altitude y_m at maximum deceleration, $y_m = y_p + s_m^{*2}/k$. It is possible to find V_m by using either of the two theories outlined previously. It is found that

$$V_m/V_p = (V_1/V_2)^{(1/2)\mathrm{erf}(s_m^*)} \qquad (8)$$

where erf(u) is the error function. The perigee velocity V_p is found by the symmetry of Eq. (1) to be simply, $V_p^2 = V_1V_2$. The deceleration at perigee is given by

$$(dV/dt)_p = V_1V_2[ke/2\pi r_0(1+e)]^{1/2}\ln(V_1/V_2)$$

and finally the maximum deceleration is given by

$$(dV/dt)_m/(dV/dt)_p = [V_m/V_p]^2 e^{-s_m^{*2}} \qquad (9)$$

Equations (8) and (9) are plotted in Fig. 3.

Figures 2 and 3 are thus useful for preliminary mission planning, since all perigee quantities are known as functions of parameters of the planet and of its atmosphere, and of V_1 and V_2 which are boundary conditions for the aerobraking maneuver. The location and value of $(dV/dt)_m$ is then purely a function of V_1/V_2, and is independent of all spacecraft design parameters as well as of the atmospheric density.

Although Maday[3] has outlined a solution to the determination of $(dV/dt)_m$, his work contains only an approximate solution to Eq. (7).

Conclusions

Two simple analytic theories for ballistic aerobraking capture are equivalent. Both ignore gravity effects, the first implicitly, the second explicitly; they must thus be regarded as different formulations of a common theory. The discussion of maximum deceleration goes beyond that of Maday by giving results in terms of dimensionless quantities; for a given

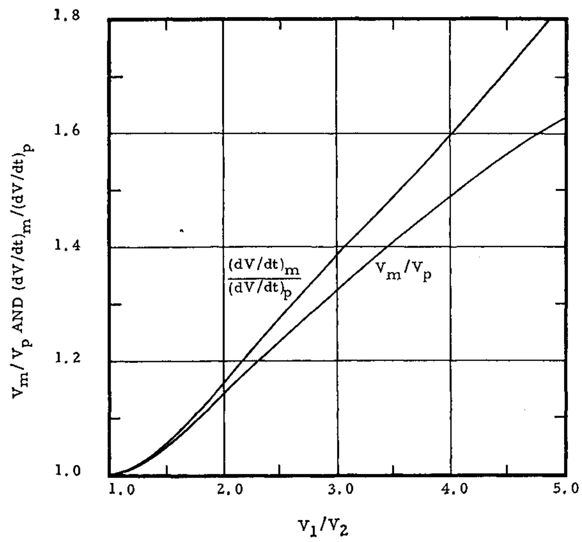

Fig. 3 Maximum deceleration and corresponding velocity, normalized with respect to deceleration and velocity at perigee.

mission, maximum deceleration is a function only of V_1/V_2, independent of ballistic coefficient. This result is analogous to a result given by Allen and Eggers in their atmosphere-entry theory.[5]

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Integrated Electronics for the Space Shuttle

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THIS Note summarizes the technical and cost goals and applicable technology improvements for the integrated electronics (avionics) of the space shuttle. The goal of the space shuttle program is to develop a low-cost reusable space transportation system for delivery of men and materials to

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Earth orbits. The avionic system hardware and software development, qualification, and production cost constitutes a major portion of the total program cost. By providing the capability for autonomous operation within the avionic system, the manpower required to support ground testing, prelaunch checkout, and mission operations can be cut significantly, and communications costs can be minimized. Sharing of existing or planned communication and navigation capabilities with other planned programs would reduce their cost to the space shuttle program, and use of common equipment on the orbiter and booster (and in certain cases on the space base) can significantly reduce development costs. Minimizing avionic system weight will permit increased payload per mission and will result in fewer flights and lower costs. Savings also might result from using existing commercial aviation, space, or military equipment such as inertial reference units, navigation aids, air traffic control equipment, communications equipment, and computers.

Technical Goals

The broad technical goals are to provide the major avionic functions for typical mission phases, summarized in Table 1, to permit two-man operation and provide airline-type operations and safety. Additional significant technical goals that affect the avionic system capability and configuration are 1) autonomous mission operations, 2) onboard abort decisions, 3) reusability for a minimum of 100 missions over a 10-yr period, 4) commonality of hardware and software, 5) commanded/automatic operation, 6) physical separation of redundant paths, 7) onboard checkout and monitoring, and 8) remote-control power switching.

Earth-based staff presently required for maintenance and prelaunch checkout must be reduced significantly; and mission control and monitoring functions, previously carried out by the Mission Control Center at Houston, Texas, must be limited to minimal surveillance on a noncontinuous basis. Communications coverage must be restricted, and checkout and inflight monitoring must be automated. Mission replanning and abort decisions must be made on the basis of onboard information.

The goals for operation with a two-man crew and safe return of the spacecraft with a single crewman imply that 1) crew decisions are required only for major events such as selection of mission phases, initiation of automated functions, and review of processed information to determine nonroutine corrective action; 2) routine functions including trend analysis, redundancy switching, transient recovery, moding, and sequencing must be automated; 3) data processing must reduce all data required for correction of an anomaly or for warning of an impending failure and present to the crew all required inputs to support the decision; and 4) all information supporting an abort decision must be presented to the crew, along with allowable alternative actions. The crew workload must be reduced by implementing a command-automated system operation, so that time-critical operations as well as rapid-turnaround requirements on the ground will be supported. This type of system provides for positive crew control over automated vehicle functions. Manual override of all automated functions is required.

The goal, airline-type safety and operations, implies sufficient redundancy to support completion of a mission and safe return of the spacecraft and crew even though some equipment may have failed. This goal has led to a desired electronic system characteristic that the system shall fail operational after the failure of any two critical components and shall fail safe after the failure of a third critical component. The trade-off studies must identify where deviations from this desired characteristic are desirable from a program standpoint. Redundancy techniques that permit automatic

Table 1 Mission phases and avionic functions

Phase	Sensors				Guidance	RCS control	Aerodynamic control	C-band	S-band	UHF	EVA/VHF	ATC/VHF	Command	Telemetry	Intercom	Air data	TACAN	ATC transponder	Landing aids	Checkout	Monitoring	Orbiter	Booster
	Docking	Rendezvous	Star	Horizon																			
Prelaunch									X				X	X	X					X	X	X	X
Boost					B	B			X					X						X	X	X	X
Orbit insertion					X	X			X					X						X	X	X	
Rendezvous		X	X		X	X		G	Ba					X						X	X	X	
Stationkeeping	X					X		G	Ba		P			X						X	X	X	
Docking	X				X	X		G	Ba				P	X	X					X	X	X	
Docked configuration								G	Ba		P		P	X	X					X	X	X	
Orbital coast			X	X		X		X			P			X						X	X	X	
Preparation deorbit			X	X		X		X					X	X						X	X	X	
Deorbit					X	X		X						X						X	X	X	
Reentry					X	X		X						X		X				X	X	X	X
Aerodynamic flight					X		X		X	X				X		X	X	X		X	X	X	X
Landing from mission					X		X		X			X	X	X		X	X	X	X	X	X	X	X
Ferry flight					X		X			X				X		X	X	X			X	X	X
Ferry landing					X		X			X		X		X		X	X	X	X		X	X	X

Ba — space base, B — booster, G — ground, O — orbiter, P — possible, X — presence of function,

RCS — reaction control system, EVA — extravehicular activity, ATC — air traffic control,

TACAN — tactical air navigation.

switchover to operational units and isolation of failed units will be required. Redundant functional paths must provide full performance capability. The redundant paths or equipment (or both) of the avionic system must be physically separated or isolated to prevent an event, (short circuit, impact, etc.) which might damage one path or piece of equipment from interfering with the proper operation of the redundant path.

The hardware technologies used for avionics must support the reusability goal ($\geq$100 missions/10 yr) throughout the storage and operating lifetime of the system. Bending-mode sensors and a load-alleviation capability in the control system may be required to ensure that the structure of the spacecraft will meet this goal.

Significant weight reductions can be made in spacecraft wiring by 1) using multiplexed data buses, in lieu of dedicated wiring, for communications among subsystems (saving over 1000 lb) and 2) providing remote-control solid-state power switching, in lieu of dedicated power leads from a central circuit breaker panel, to each piece of equipment (saving 1000 to 2000 lb). The use of remote-control power switching supports the geometrical distribution of equipment, the automated configuration control needs, and the redundancy and failure-isolation requirements.

The cost goals demand that hardware and software commonality be a technical goal. Orbiter and booster functional requirements and performance capabilities must be normalized to permit commonality. For the hardware, this practice eliminates duplicate development, qualification, and test costs and reduces a) the inventory for spare equipment; b) training costs for maintenance personnel, c) the number of maintenance personnel, equipment, and facilities; and d) the requirements for crew training facilities and software. The use of common flight and ground software can reduce programing and verification costs, ensure ground-space compatibility, and provide flexibility to make mission changes.

Integrated Electronics

The requirements of two-man control, autonomous operation, and airline-type operations and safety have resulted in the need for a redundant, automated system capable of processing large amounts of data. This type of system requires integration of the subsystem electronic equipment under one supervisory tool, an executive computer and its controls. A multiplexed data bus and standardized interface units complete the integration. The subsystems are essentially collections of the classical equipment. Thus, an integrated electronics system implies a data management system, communication channels, and interface channels to manage the equipment of the avionic system and the other elements of the spacecraft. It relieves the crew of routine tasks and decisions and facilitates ground checkout, thus supporting minimum maintenance and 2-week turnaround requirements. Furthermore, it permits mission changes without major hardware changes, keeps the major portion of the avionic system free of spacecraft detail until late in the design phase, and permits the introduction of new technology equipment and additional equipment late in the development cycle.

Methodology

Three types of decisions that must be made in selection of the avionic equipment and system concepts for the space shuttle follow. 1) Selection of individual pieces of equipment is made on the basis of technical parameters and cost. Key technical parameters are identified, and the data on them for the available alternatives are accumulated and evaluated to select the most technically desirable system. 2) Determination of the degree of centralization, along with the computer configuration and organization, represents a more complex level of decision. In this level, at least the technical parameters of equipment and system organizations, the software complexity, and the relative costs must be considered. 3) Selection of an optimum avionic system to provide a) the required performance capability with adequate redundancy and b) minimal program cost represents the most complex and ultimate decision that must be made.

One method of evaluation is to reduce all parameters to a cost basis and to evaluate by computer the relation between the variations of cost and the degree of achievement of technical goals. Another method would provide selection of an avionic system within the cost goals and with optimized performance.

Technology

The NASA Space Shuttle Integrated Electronic System Technology Committee has consolidated the technology development requirements. These programs have been, are being, or will be pursued through funded and in-house studies. Administration and evaluation of each program has been assigned to a single NASA center.

The first group of studies supports weight reduction. A breadboard will be fabricated to evaluate the multiplexed data bus 1) in a large integrated system to verify techniques for multiplexing and for interfacing with subsystems and 2) in a closed-loop control system simulation to develop confidence in the application of this technology to critical control systems. To maximize the benefits of decentralized power switching, additional effort to reduce power losses in, to extend the operating range of, and to develop reliability and application data for a.c. and d.c. solid-state circuit breakers is required. Terminal area navigation techniques, guidance and control techniques for approach and landing, and advanced automatic landing systems are being analyzed and evaluated in simulations and test programs so that the feasibility of landing an unpowered orbiter can be determined.

The second group of studies, supporting the autonomy and two-man crew requirements, will establish the technology and experience necessary to automate checkout and monitoring. State-of-the-art surveys and detailed investigations of the techniques for built-in tests and/or self tests are being pursued. Techniques are being developed for integration of the avionic equipment and of the avionics with the spacecraft equipment in a manner that will permit their control by a two-man crew. A major effort is the development of the software to provide a man-machine interface through multipurpose redundant displays and controls.

The third group of studies involves the development of criteria for the evaluation of various avionic system configurations and evaluation of techniques for meeting the reliability and redundancy goals. Technology trade-off studies are being conducted at the system, equipment, and component levels. Methods to achieve the use of common avionics in the orbiter and booster are being explored.

Finally, the following component-level technology and state-of-the-art studies are underway: 1) extension of the communications hardware capability to 5.9–6.4 GHz for compatibility with Intelsat IV by development of a 100-w traveling-wave tube and a parametric amplifier with less than 2 db of noise; 2) extension of an existing laser system for use as a rendezvous and docking sensor; 3) development of color cathode-ray tubes; 4) improvement of antenna and antenna coating technology; 5) improvement of the states of art for a) instrumentation sensors, b) testing and screening of medium-scale integration and large-scale integration, and c) inverters, d.c.-d.c. converters, and regulators; 6) improvement of capacitors and transistors for power conditioning; 7) evaluation of inertial sensors and alternate systems;

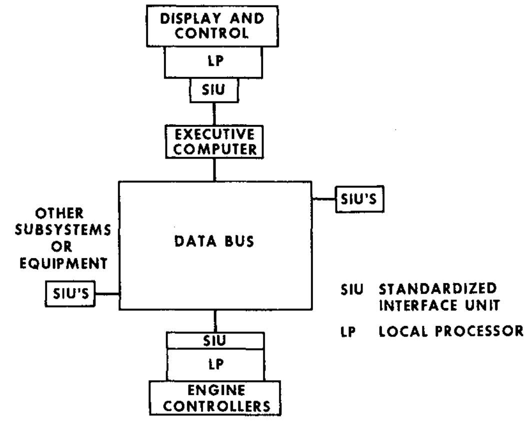

Fig. 1 Potential base-line system configuration.

and 8) evaluation of the state-of-the-art of 10^7–10^9 bit mass storage devices.

Current Studies

Two Space Shuttle Phase B program definition studies (including the avionic system, its performance requirements, and its interfaces with the spacecraft) are underway. Each of these contractors is conducting the following major trade-off studies as a part of the avionic system effort.

One study is to provide the data for determining which functions should be centralized and which should be decentralized. The location of onboard data processing (the computation configuration) and the organization of the computer complex (or complexes) is to be explored. Factors that are involved include computation requirements and data rates of subsystems, geographical distribution of equipment, failure isolation and redundancy switching, configuration control and power switching, and onboard checkout. Software complexity and cost will be major factors in this study.

Alternative methods for implementing the data bus and techniques for interfacing a variety of equipment with a standard data bus interface are to be evaluated.

Methods for executing automated onboard checkout, for test initiation, control, and stimuli generation, and for monitoring for caution and warning purposes, shall be evaluated. Built-in test/self-test feasibility and desirability shall be evaluated. The extent of crew participation shall be determined.

Automated and manual techniques for configuration and sequencing control are to be compared. The degree of crew participation and workload, and the systems and software impact, are to be evaluated. Redundancy techniques are to be evaluated, and failure isolation, redundant path switching, and methods for checkout of redundant paths are to be considered.

The crew decision and control requirements for integrated displays and controls and methods for integration and interfacing of sensors and actuators with the integrated electronic system are to be evaluated. The man-machine workload balance to provide autonomous two-man operations is to be established. The requirements for and interfaces between the shuttle, ground facilities, and communication satellites for communications and tracking are to be evaluated to select the most cost-effective system.

The centralization of power conversion vs the conversion within subsystems is to be evaluated with regard to overload and short-circuit protection, and the power quality requirements are to be established.

Studies of total avionic systems being conducted in house by NASA include an independent assessment of requirements; trade-off criteria; alternate hardware, software, and system concepts; selection and definition of a base-line system; and so forth. Critical system components are being breadboarded and evaluated.

The results of the contracted Phase B studies, the technology developments, and the in-house studies are being analyzed and evaluated by NASA and will be used as a basis for the requirements of the Phase C and D avionics.

Concluding Remarks

The Phase B studies have just begun and results are not yet available. The results to date of the in-house program at the NASA Manned Spacecraft Center support the base-line system, for which the potential system configuration is shown in Fig. 1. A single computer configuration would provide the major portion of the computation and avionic system management capability. Main memory requirements are of the order of 64,000 words of 32 bits. Mass memory requirements are of the order of 300,000 words of 32 bits. Computer instruction throughput is estimated to be of the order of 15 megabits/sec.

Localized requirements for high-volume data processing exist in two areas and could be served by local processors of intermediate capability: the display and control system, for data formatting and symbology generation, and the interface between the rocket engine controllers and the avionic system.

Separate data buses will run forward and aft from the central computer location in the avionic equipment bay. The buses will be quadruply redundant, and each bus will be physically separated from the others. Subsystems will communicate with each other through the central computer by means of the data bus. Data rates on individual branches are expected to be 100,000–200,000 bits/sec. A design goal capacity of 1–5 megabits/sec for the data bus is feasible with present technology. The use of the multiplexed data bus will permit growth of the avionic system to meet growing mission requirements. New or different subsystems or equipment, may be added by attaching them to existing standardized interface units (SIU's) on the bus. This capability supports the requirement to level out program costs over a number of years by delaying development of complex or newly defined equipment. The SIU's will provide: the encoding or decoding required for the interface, address recognition, signal conditioning, and local data processing. The latter, for most SIU's, will be of a limited nature but will provide: mode control for operation, checkout, and redundancy switching; limit checking, trend analysis, etc., for checkout and status monitoring; and other localized requirements for data processing.

The display and control system might include multipurpose cathode-ray tubes for flight situation displays, numerical displays, alphanumeric displays for discrete information, and multifunction reformattable controls. The navigation sensors might include initially a horizon scanner and a star tracker, and later, a cooperative rendezvous sensor and a docking sensor. This equipment will be mounted on a unitized pointing system. Bending-mode sensors may be used, and the control system probably will be a redundant fly-by-wire system. The navigation aids might include a multilateration beacon system and radar altimeters.

The communication system will possibly provide for extravehicular-activity communications, air-traffic-control communications, S-band communications with the ground and the space base and between the orbiter and the booster, a low data rate up-down command-telemetry capability, a command decoder, a recovery beacon and crash recorder, and intercom for crew and passengers.

The value of the multiplexed data bus in supporting the spreading of development costs over a longer period of time is apparent.